Susceptibility of Grade 8 Fasteners

to Stress Corrosion Cracking

by

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SUMMARY

A brief historical review of the development of Plane Strain, Elastic, Fracture Mechanics is presented. Fracture toughness parameter, K_Ic* and stress corrosion cracking threshold level [parameter] K_Iscc are introduced and elaborated upon.

The use of Fracture Mechanics - via the K_Iscc concept - to assess the resistance of low alloy steel to stress corrosion cracking in hostile environments is outlined and referenced.

Based on the data presented in this report, it is concluded that zinc plated, low alloy steel fasteners below one inch in diameter, in the yield strength range of 130 to 160 ksi are immune to stress corrosion cracking in sea water environment.

INTRODUCTION

Sharp crack fracture mechanics originated from a crack propagation concept proposed by A. A. Griffith[1] on February 26, 1920, which states: "An existing crack will propagate in a cataclysmic fashion if the available elastic strain energy release rate exceeds the increase in surface energy of the crack". To paraphrase, one can say that "An existing crack will propagate if thereby the total energy of the system is lowered".

The Griffith concept may be quite simply represented by the following equation:

$$\frac{d}{dt}\left[-\frac{\sigma^2 \pi a^2}{E} + 4 a T \right] = 0 ,$$

which is graphically shown in Figure 1. The first term in the parentheses represents the elastic energy loss, while the second term represents the energy gain of the system due to the creation of a new surface (i.e. "surface energy" due to the imbalance of the atoms on the surface).

This energy balance concept was seriously challenged with the advent of X-ray diffraction, when it was shown[2] that even brittle materials undergo some plastic deformation on the fracture surface.

*The symbols used in this report are listed and defined in Table I.

The concept was modified to account for the plastic deformation and was restated as follows: "The energy balance is between the strain energy stored in the specimen (or the load carrying member -BH) and the surface energy plus the work done in plastic deformation[3].

The dilemma of the relative importance of the surface energy versus the plastic deformation energy becomes moot if the energy concept is replaced by the stress-strain concept. In 1957 Irvin[4] showed that the energy approach, is equivalent to a stress-intensity approach, according to which fracture occurs when a critical stress distribution, characteristic of the material, is reached. Linear theory of elasticity provides a unique and single valued relationship among stress, strain and energy. Therefore, a fracture criterion expressed in terms of an energy concept has its equivalent stress and strain criteria, all of which are mathematically indistinguishable.

Using Westergaard's[5] crack tip stress distribution, shown in figure 2, the following three equations are written.

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right]$$

$$\sigma_x = \frac{K}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right]$$

$$\tau_{xy} = \frac{K}{\sqrt{2\pi r}} \left[\sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right]$$

Looking at the above equations it becomes obvious that the stress goes to infinity as "r" approaches zero. This however, is precluded by the onset of plastic deformation at the crack tip. Since this plastic enclave is embedded within a large elastic region of material and is acted upon by either biaxial (σ_y, σ_x,) or triaxial (σ_y, σ_x, σ_3) stresses, the extent of plastic strain within this region is suppressed.[6] Because of constrains in the "z" direction, a triaxial state of stress at the crack tip - which is a normal condition for thick bodies - results in biaxial or plane strain condition. This principle is best illustrated in figure 3.[7] Figure 3 illustrates an axially loaded member. The stress concentration effect of the notch or crack tip causes high longitudinal stresses at the crack tip. These stresses decrease as

2

the distance from the crack tip increases. In accordance with the
Poisson effect (conservation of volume), lateral contractions
in the ("3" and "x" directions) must accompany these longitudinal
stresses, but the lateral contractions in the width and thickness
directions of the highly stressed material at the crack tip is
restricted by the smaller lateral contractions of the lower
stressed material. Consequently, tensile stresses are induced in
the "x" and "z" directions so that a severe triaxial state of
stress is present near the crack tip with a concurrent biaxil or
plane strain.

The $K_I c$ Concept

Looking at the three Westergaard's equations it becomes
obvious that the stress intensity factor "K" is a function of the
applied stress and crack geometry and, for a crack of length 2a in
an infinite plate, is given by:

$$K = \sigma \sqrt{\pi a}$$

To take account of finite plates and various geometries (and crack
positions) of the load carrying member , the above equation for
plane strain - triaxial stress condition may be written as:

$$K = C\sigma \sqrt{\pi a}$$

or

for a condition where the crack is unstable (onset of catastrophic
fracture)

$$K_I c = C\sigma \sqrt{\pi a_{cr}}$$

This basic equation can be modified to fit various geometries
of the load carrying members. However, for the elastic fracture
mechanics to apply two conditions must always be present:

1. Plane strain, and

2. an existing crack or a crack-like defect.

For a round, notched bar, shown in figure 4, subjected to a
uniaxial tensile stress, (that is, K_{II} in plane shear mode and K_{III}
in antiplane shear [~ torsion-like -B.H.] mode are equal to zero) -
Paris and Sih [8] developed the following equation:

3

$$K_I = \left[\sigma \sqrt{\pi D} \right] \left[f\left(\frac{d}{D}\right) \right]$$

The first part of the above equation is straight forward, the second part, however, is not. The second part of the equation, however, can be calculated by examining what happens at the limits, i.e. when "D" approaches infinity ($D \rightarrow \infty$) and when the ratio $f(d/D)$ approaches 1 ($f(d/D) \rightarrow 1$). When the mathematics are worked out [8], the results are shown in Table II. It must be understood that Table II solutions are not analytical, i.e. there is some uncertainty attached to the numbers. Generally, depending on the $(\frac{d}{D})$ range, the accuracy is on the order of $\pm$ 2 to 5%.

Carefully considering the following:

1. $K_I c$, a critical stress intensity factor generally inversely proportional to the yield strength of the material in question.

2. Crack, or crack-like defect, dimension, which for a notched bar (i.e. a fastener) is simply a thread depth (ratio of the minor and major diameters).

3. Applied load, which for the bolted joints is simply applied torque stress.

4. Major diameter of the bolt, which (in combination with the yield strength of the bolt material) is a function of the plane strain condition (which, in turn, justifies fracture mechanics approach); in light of:

$$K_I = \left[\sigma \sqrt{\pi D} \right] \left[f\left(\frac{d}{D}\right) \right] \quad \text{or}$$

$$K_I c = \left[\sigma \sqrt{\pi D} \right] \left[f\left(\frac{d}{D}\right) \right]$$

and   Table II

4

a series of curves may be constructed relating K_Ic, yield strength, diameter and the applied stress (from the applied torque) of a particular fastener.

W. S. Pellini[9] did extensive work in this field and developed an approach to the solution of practical problems which he called Ratio Analysis Diagram Concept (RAD). These diagrams, by way of an example, are shown in figures 5 and 6.

K_Iscc Concept

From the viewpoint of plane strain, linear elastic fracture mechanics K_Ic can be considered as a limiting strength of the load carrying member with a crack, or a crack-like defect. However, K_Ic approach completely disregards the environment in which the load carrying member operates.

Stress corrosion cracking is a localized damage phenomenon which appears to depend upon, among other things, the magnitude of stress in the vicinity of a crack tip. Since the stress intensity concept of fracture mechanics provides a quantitative measure of the magnitude of crack-tip stresses, it is reasonable to expect that stress corrosion cracking behavior ought to be related to the corresponding applied stress intensity factor.

In a detailed examination of this hypothesis, Johnson and Willner[10] demonstrated that both the onset of stress corrosion cracking in the presence of a crack (or a crack-like defect) as well as the rate of subsequent crack growth (da/dt) was dependent upon the applied stress intensity factor K. Since this early work, an extensive amount of additional data have been developed which clearly show that the applied stress intensity factor is the controlling stress parameter for stress corrosion in the presence of a crack-like defect.

A material constant, K_Iscc, which characterizes stress corrosion cracking is defined as: "The value of plane strain stress intensity factor (level) below which an existing crack (or a crack-like defect - B.H.) will not grow due to stress corrosion."[11]

No standard test method currently exists for K_Iscc measurement; however, almost all standard plane strain fracture toughness test specimens can be adapted to stress-corrosion cracking testing.[12]

Some of the specimen configurations for stress corrosion cracking are shown in Figure 7.

Evaluation of Grade 8 Bolts via $K_I$scc Concept

The mechanical property parameters of Grade 8 bolts are given by SAE J-429 specification as:

Tensile Strength.......................150 ksi minimum
Yield Strength.........................130 ksi minimum
Elongation.............................12% minimum
Reduction of Area......................35% minimum
Hardness...............................39 HRC maximum

Taking the worst possible case, from the viewpoint of fracture mechanics, of a bolt with the HRC 39 hardness value, we obtain the following strength values:

Tensile Strength.......................180 ksi [13]
Yield Strength.........................160 ksi [14]

Reconsidering Table II and substituting $K_I$scc into the

$$K_I = \left[\sigma \sqrt{\pi D} \right] \left[f\left(\frac{d}{D}\right) \right] \quad \text{equation}$$

we arrive at the following relationship:

$$K_I scc = \left[\sigma_{a.s.} \sqrt{\pi D} \right] \left[f\left(\frac{d}{D}\right) \right] \quad \text{equation;}$$

where:

$\sigma_{a.s.}$ = The applied stress or torque stress, which corresponds to Grade 5 applied stress.

Again, taking the worst possible case for a one-half inch Hex Head Cap Screw with machined (cut) threads, 1/2 in. - 13 UNC - 2A

$$\sigma_{a.s} = 85 \text{ ksi}$$

$$\sigma_y = 160 \text{ ksi}$$

$$D = 0.50 \text{ in.}[15]$$

$$d = 0.41 \text{ in.}[15]$$

$$f(\frac{d}{D}) = f(\sim\frac{.41}{.50}) = 0.22 \text{ (from Table II)}$$

Therefore:

$$K_I scc = \left[(85)\sqrt{\pi(.50)} \right] \left[0.22 \right]$$

$$K_I scc = 23 \text{ ksi}\sqrt{in}$$

Therefore, for a 1/2 in. screw, we need the $K_I scc$ to be at least 23 ksi$\sqrt{in}$ in order to be safe, i.e. for the screw to be resistant to stress corrosion attack in sea water; and this is the worst possible case.

Similar calculations may be performed for a 5/8 in. and 3/4 in. Hex Head Cap Screws with the following results:

1. For a 5/8" (machined threads) hex head cap screw.

5/8" - 11 - UNC - 2A,[15] with the following diameters:

$$d = 0.52 \text{ in.}$$

$$D = 0.62 \text{ in.}$$

$$K_I scc = \left[(85)\sqrt{\pi(.62)} \right] \left[f(\frac{d}{D}) \right] = \left[118.6 \right] \left[.22 \right] = 26 \text{ ksi}\sqrt{in}$$

2. For a 3/4" (machined threads) hex head cap screw

$$3/4" - 10 - UNC - 2A^{15}$$

$$d = 0.64 \text{ in.}$$

$$D = 0.75 \text{ in.}$$

$$K_I scc = \left[(85) \sqrt{\pi (.75)} \right]\left[f(\frac{d}{D}) \right] = \left[130.4 \right]\left[.22 \right] = 29 \text{ ksi}\sqrt{\text{in}}$$

Solution of Stress Corrosion Problems via Ratio Analysis Diagrams

As was mentioned heretofore, W. S. Pellini[9] is credited with originating the Ratio Analysis Diagram concept which is used in the solution of real problems encountered in the field by load carrying material systems. Pellini's RAD concept was considerably expanded and popularized by L. Raymond, [16], [17] who applied the concept to the solution of stress-corrosion-cracking problems in fasteners. One of L. Raymond's diagrams is shown in figure 8. Essentially Figure 8 is a graphical representation of Paris and Sih [8] equation showing the demarcation between brittle (where fracture mechanics applies) and ductile (where plane strain elastic fracture mechanics does not apply) failures.

To investigate the susceptibility of relatively small diameter low alloy steel fasteners in the yield strength range of 130 to 160 ksi to stress corrosion cracking in sea water environment, we expended a considerable effort and reviewed the published literature on this subject. This referenced information is shown in Table III. Carefully examining Table III, it appears obvious that for zinc plated low alloy fasteners in the yield strength range of 130 to 160 ksi a $K_I scc$ value of about 40 ksi $\sqrt{\text{in}}$ is most appropriate. This value is taken from Shih and Clark's yield strength versus $K_I scc$ relationship which appeared in the Atlas of Stress-Corrosion and Corrosion Fatigue Curves, an American Society of Metals publication edited by A. J. McEvilty, Jr. (shown in this report as reference #18), and is shown here as figure 9.

Taking the value of 40 ksi $\sqrt{\text{in}}$ (for $K_I scc$) for 1/2 in. fastener for a as/ys line = 0.5 - we are well within the ductile fracture region as shown in figure 10. Figure 10 shows that we are well within the "safe region" even if we take an extremely conservative approach and assign a value (for $K_I scc$) to our 1/2 fastener as 30 ksi $\sqrt{\text{in}}$. Furthermore, even 3/4 in diameter fasteners are in the "safe" zone with a considerable safety factor. It is only after the fastener

8

exceeds 1 in. in diameter (and, in combination with the yield strength, plane strain condition begins to take over) that we are approaching brittle failure and, therefore, the fastener may become susceptible to stress corrosion cracking (as defined by fracture mechanics).

DISCUSSION

Examining the $K_{I}scc$ data presented in Table III in light of Paris and Sih's equation, a number of generalizations may be made:

1. Low alloy steel fasteners in small diameters heat treated to the yield strength range of 130 to 160 ksi are immune from stress-corrosion cracking as defined by fracture mechanics.

2. As the diameter of the heretofore mentioned fastener increases (i.e. above one inch), the fastener begins to approach plane strain state and may become susceptible to stress-corrosion-cracking.

3. Obviously, plane strain state is a function not only of the diameter but also of the strength level of the fastener as defined by the yield strength. This is starkly evident from Table III, where it is shown that there is catastrophic deterioration of the $K_{I}scc$ parameter for low alloy steels heat treated beyond 180 ksi yield strength.

Having analyzed the susceptibility or, rather, lack of susceptibility, of 130 to 160 ksi yield strength fasteners to stress corrosion cracking in sea water environment from the viewpoint of fracture mechanics, let us discuss this approach from a different perspective. In this brief analysis an impression may have been conveyed that the fracture mechanic's approach to stress-corrosion cracking is universally accepted. This, however, is not the case.

There are many objections, some of them quite serious, to the fracture mechanics approach to stress-corrosion cracking. The most serious of these objections are:

1. The astonishing oversimplification of a very complex phenomena, and

2. A tremendous variance of experimental data obtained on ductile or semi-ductile materials.

Let us examine these objections in detail. First of all, let us enumerate the variables that definitely affect the stress-corrosion cracking behavior of metals and comment on them:

9

a. Composition. Composition of a particular alloy (i.e. the level of nonmetallics, etc.) is extremely important in both $K_I$scc and da/dt considerations.

b. Strength level. Obviously, extremely important. Generally, strength level (as measured by the yield strength) is inversely proportional to $K_I$scc.

c. Directional effects. Can be very important in materials which exhibit directional effects on other properties (i.e. grain orientation, etc).

d. Processing. Residual stresses, for example, can either enhance or retard stress-corrosion-cracking behavior (i.e. thread rolling in fasteners definitely retards the onset of stress corrosion cracking).

e. Environmental chemistry. Extremely important; a slight change in chemistry can significantly alter stress-corrosion-cracking behavior.

f. Applied Potential. The ufe of cathodic protection has a definite effect on the susceptibility to SCC. This effect is most noticeable in high strength steels.

g. Temperature. Temperature is an indefinite variable. Usually, with an increase in temperature the resistance to SCC increases (perhaps due to the drop in yield strength of the material).

h. Pressure. Obviously, with an increase in pressure of the environment one would expect the susceptibility to SCC to increase.

i. Exposure Time. Very important in both testing and application considerations. Generally, larger exposure times yield more accurate design data.

j. Section size. Deviation from plane strain condition invalidates the fracture mechanics approach; and yet, a number of materials exhibit stress-corrosion cracking behaviour under elastic-plastic conditions.

10

k. Loading spectrum. Can have a significant effect (i.e. prior loading in air can retard SCC, overloads can retard SCC, and so on).

The above are just a few of the variables that have an effect on the susceptibility of a particular material to stress corrosion cracking. In the case of fasteners, for example, a number of additional variables come to mind, namely:

1. Rolling or machining of threads.

2. Thread root radius.

3. Type of heat treatment given to the raw stock (i.e., in the case of carbon or low alloy steels, has the steel been normalized?, etc.)

4. The distribution of load (that is, torque stress) on the threads.

5. Possible relaxation (due to vibration or other factors) of the applied load.

6. Integrity, or lack of integrity, of the cathodic protection coatings, and so on.

The second objection to the fracture mechanics approach (to the solution of stress corrosion cracking problems in metals) is a c nsiderable variance in test data. Observing various values for $K_{I}scc$ in Table III, one can (and should) conclude that this concern is valid. While one may attribute the variance in the data (and rightfully so!) shown in Table III, to the inclusion or exclusion of the variables (during testing) listed heretofore, the fact remains that the tests for stress-corrosion cracking give, at best - an indication of how a load carrying member may perform in service!

Perhaps at this juncture it would be appropriate to quote R. N. Parkins, [39] [who wrote in his analysis of the International Symposium held in Cincinnati, Ohio, on October 21-24, 1991 under the general heading "Fundamental Aspects of Stress-Corrosion-Cracking"] "For some 100 years, the problem of environment induced brittle failure of normally ductile alloys has intrigued and per `exed researchers. A variety of mechanisms have been invoked, and w. le many of them seem to be operative in some instances, they do not all universally apply." And, "In service situations, the usually carefully controlled environmental, material, and stressing conditions involved in lab experiments will rarely be present, and it should not be surprising that nominally

11

identical plants do not always follow a predictable path in relation to cracking." It may be concluded, therefore, that experience in the field is far superior to any possible laboratory test results; since the number of tests necessary to reproduce all the possible permutations and variations in the field would, essentially, be limitless.

CONCLUSIONS

Based on the literature search, presented in this paper, and based on the experience in the field it is concluded that zinc plated, hex head cap screws below one inch in diameter, in the yield strength range of 130 to 160 ksi under the applied torque stress of 85 ksi are immune from stress corrosion cracking in sea water environment.

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Table I

Symbols Used in this Report

Symbol		Definition
a	$=$	Crack dimension
σ	$=$	Stress
σ_y	$=$	Yield Strength (or stress)
E	$=$	Modulus of Elasticity
T	$=$	Surface tension
K	$=$	Stress intensity factor
C	$=$	Geometrical constant
$K_{I}c$	$=$	Critical, tensile mode, plane strain, stress, intensity factor (a material constant)
a	$=$	Crack dimension
a_{cr}	$=$	Critical crack dimension (at this dimension the crack becomes unstable resulting in a catastrophic failure)
D	$=$	Major diameter of a notched bar (fastener)
d	$=$	Minor diameter of a notched bar (fastener)
$\dfrac{da}{dn}$	$=$	Crack growth per cycle of stress
$\dfrac{da}{dt}$	$=$	Crack growth per unit time
$K_{I}scc$	$=$	Plane strain, stress intensity factor below which an existing crack (or a crack-like defect) will not grow in a hostile (corrosive) environment; sometimes referred to as: "Stress Corrosion Cracking Threshold Level"
$K_{I}eac$	$=$	Same as $K_{I}scc$ (eac stands for environment assisted cracking)
$\sigma_{a.s}$	$=$	Applied stress (for a fastener it may be torque stress).

Table II

Stress Intensity Factor Coefficients for Notched Round Bar

$\dfrac{d}{D}$	$f\left(\dfrac{d}{D}\right)$
0.00	0.000
0.10	0.111
0.20	0.155
0.30	0.185
0.40	0.209
0.50	0.227
0.60	0.238
0.65	0.240
0.70	0.240
0.75	0.237
0.80	0.233
0.85	0.225
0.90	0.205
0.95	0.162
0.97	0.130
1.00	0.000

Table III

$K_I$scc Data for Carbon and Low Alloy Steels
Heat Treated to the Yield Strength of 160 ksi and Higher

$K_I$scc (ksi$\sqrt{in}$)	Description of the Test	Reference
40	160 ksi Yield Strength 4340 steel in sea water + zinc electrode. Long time steady load tests and rising load tests.	18
22	187 ksi yield strength, low alloy steel in 3.5% NaCl solution at room temperature.	19
45	160 yield strength 4340 steel-axial wedge loading of cylindrical specimens in sea water.	20
43	160 yield strength low alloy steel tested in 3.5% NaCl (open circuit) solution.	21
81,82,97	160 yield strength 4340 steel, rising load, WOL specimens in synthetic sea water.	22
42	39 HRC (160 yield strength) "Plot of Threshold Stresses for Stress Corrosion Cracking in Low Alloy Quenched and Tempered Bolting Materials with Different Hardness Levels.	23
50	$K_I$scc - Yield Strength Relationship (at 160 ksi Yield Strength) For Type 4340 Steels with Different Austenitic Grain Sizes.	24

<u>Table III - Continued</u>

50	Threshold Stress Intensity Values for Stress Corrosion Crack Propogation in Salt Water of Some Commercial Steels (160 yield strength).	25
50	Effects of Quiescent Distilled water containing 3.5% NaCl and Flowing Sea Water on the Threshold Stress-Intensity Parameter for Stress-Corrosion Cracking of 4340 steel (at 160 ksi Yield Strength).	26
12.5 ± 1	$K_I$scc in Sodium Chloride Solution for 835 M 30 (Ni-Cr-Mo Low Alloy Steel - B.H.) Material (Notched Transversely) at the Yield Strength of 196 ksi.	27
13.0 ± 1	$K_I$scc in Sodium Chloride Solution for 835 M 30 Material (Ni Cr Mo Low Alloy Steel - B.H.) Notched Longitudinally at the Yield Strength of 209 ksi.	27
12.0 ± 1	$K_I$scc in Sodium Chloride Solution for 9 Ni 4 Co 0.45C Martensitic Steel at the Yield Strength of of 237 ksi.	27
13.0 ± 1	$K_I$scc in Sodium Chloride Solution for 9 Ni 4 Co 0.45C Bainitic Steel at the Yield Strength of of 230 ksi.	27
20 ± 3	Effect of Silcon Content on Fracture Toughness and Threshold Stress Intensity for Crack Growth for 4340 Steel at 230-240 ksi Yield Strength in 3.5 NaCl Solution.	28
24	4340 Steel Heat Treated to 230 ksi Yield Strength in 3.5% NaCl.	29

Table III - Continued

25	Effect of Gas (H_2S) Pressure on Apparent K_{Iscc} in 4340 Steel Heat Treated to 180 ksi Yield Strength.	30
60	The Effect of Hydrogen Gas on High Strength Steels (181 ksi Yield Strength Ni Cr Mo V Low Alloy Steel).	31
22	The Application of the K_{Iscc} Concept to Very Small Defects (Lowest of Nine Values for 4340, 180 ksi Yield Strength Steel in 5 psig H_2S, 80°F Environment - B.H.).	32
26	The Application of the K_{Iscc} Concept to Very Small Defects (Average of Nine Values for 4340, 180 ksi Yield Strength Steel in 5 psig H_2S, 80°F Environment - B.H.).	32
14	The Application of the K_{Iscc} Concept to Very Small Defects (Lowest of 13 values for 4340, 215 ksi Yield Strength Steel in 5 psig H_2S, 80°F Environment - B.H.).	32
17	The Application of the K_{Iscc} Concept to Very Small Defects (Average of 13 values for 4340, 215 ksi Yield Strength Steel in 5 psig H_2S, 80°F Environment - B.H.)	32
25	Fatigue and Corrosion Fatigue Crack Growth of 4340 Steel at Various Strengths (180 ksi Yield Strength in 3% NaCl solution).	33
8	The Influence of Applied Polarization on the Stress Corrosion Properties of a High Strength Steel (The lowest of 5 values; 750 mv cathodic in 3.5% NaCl + H_2 + H_2S for 210 ksi Yield Strength Cr Mo V Low Alloy Steel - B. H.)	34

Table III - Continued

48	Environment Induced Cracking in High Strength Bolting Materials 4340, 160 ksi Yield Strength in Sea Water - B.H.)	35
41	$K_I$scc in 1.5 psi H_2S Gas (Precracked) (160 ksi Yield Strength, ASTM A645, 5% Ni, Low Alloy Steel - B.H.)	36
8.5	4340 Steel Heat Treated to 194 ksi Yield Strength in NaCl Solution	37
15	4340 Steel Heat Treated to 245 ksi Yield Strength in NaCl Solution	37
5	4340 Steel Heat Treated to 225 ksi Yield Strength in NaCl Solution	37
11	4340 Steel Heat Treated to 200 ksi Yield Strength in Sea Water	37
27	4340 Steel Heat Treated to 175 ksi Yield Strength in Sea Water	37
59	4340 Steel Heat Treated to 150 ksi Yield Strength in Sea Water	37
55	Effect of Yield Strength on $K_I$eac (in Flowing Sea Water) for (160 ksi Yield Strength 4340 Steel -. B. H.)	38
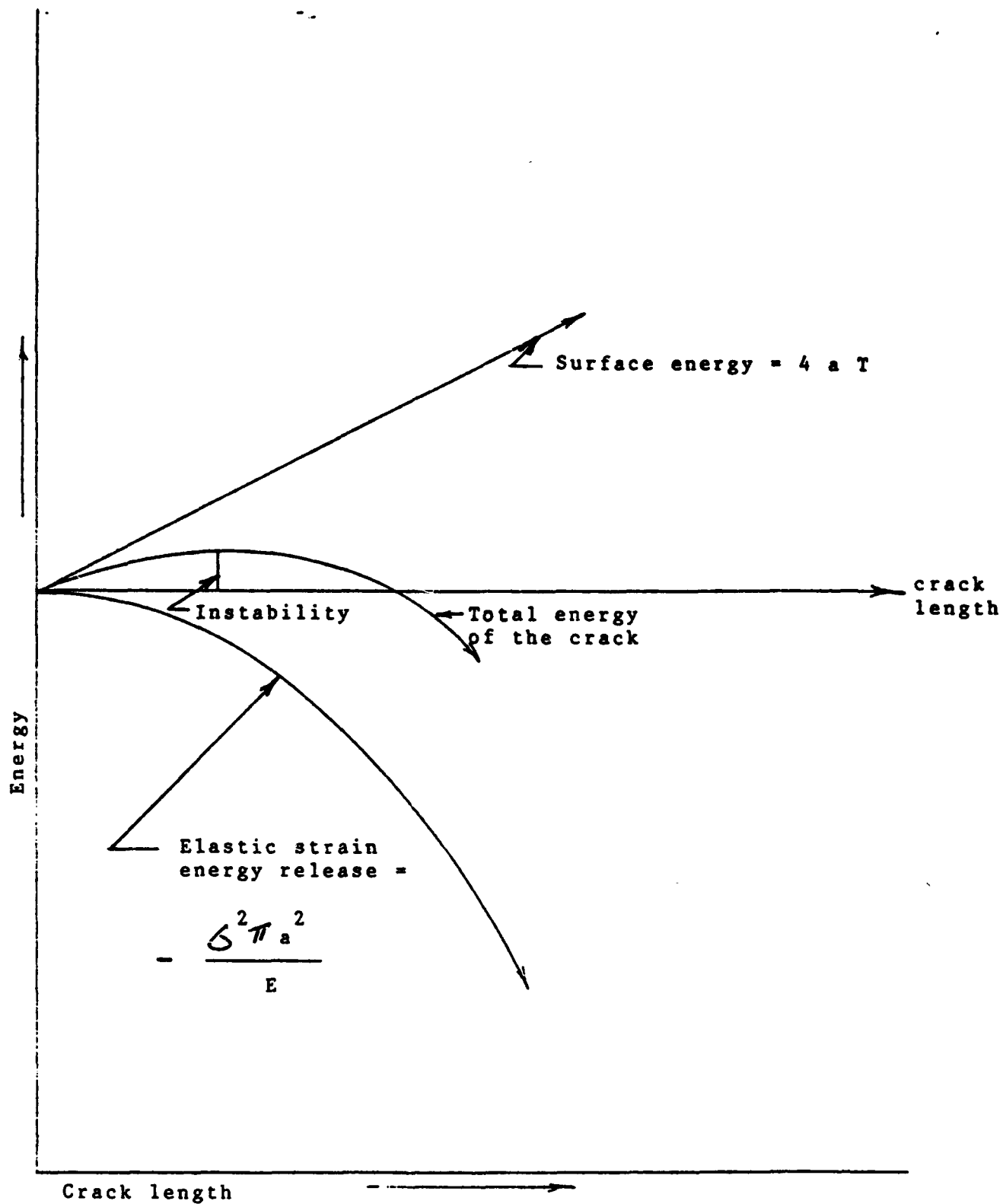
Figure 1 - Griffith Energy Balance of a Crack in an Infinite Plate
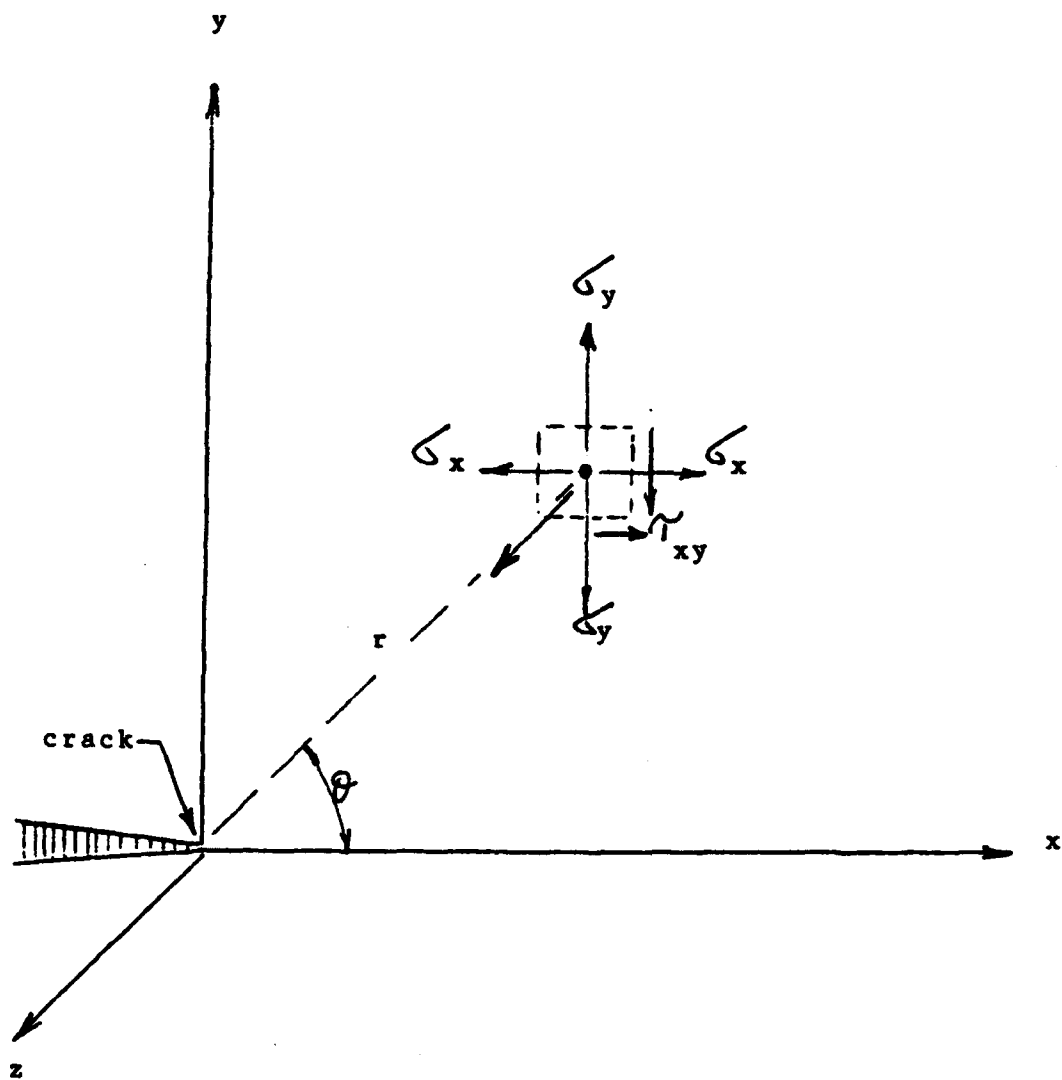
Figure 2 - Westergaard's Stress Distribution at the Crack Tip.
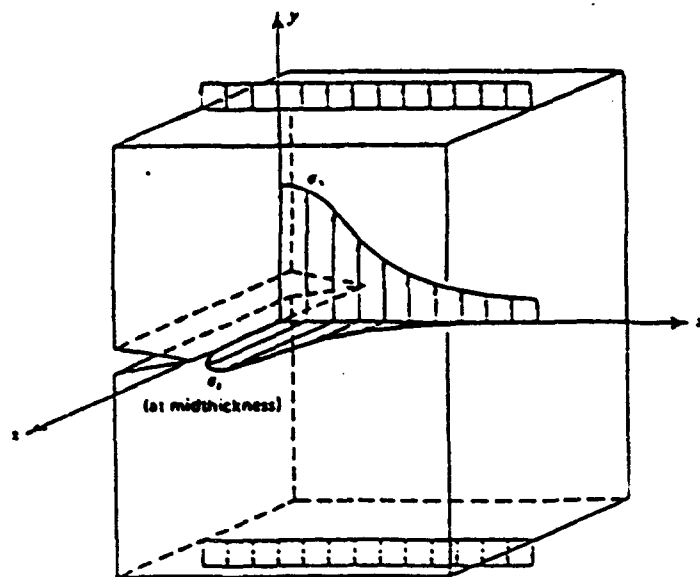
Figure 3 - State of Stress at the Root of a Crack (notch) Under
Uniaxial Loading   (y direction). σ_y (uniaxial tensile
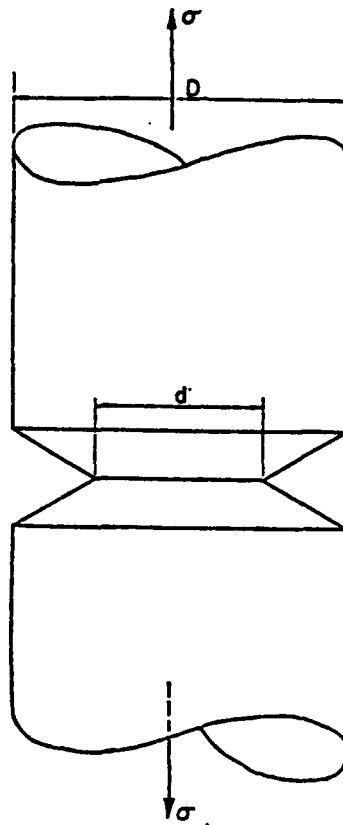load) induces σ_x and σ_3 (σ_x is not shown in this sketch).

Figure 4 - A Circumferentially "Cracked" Round Bar
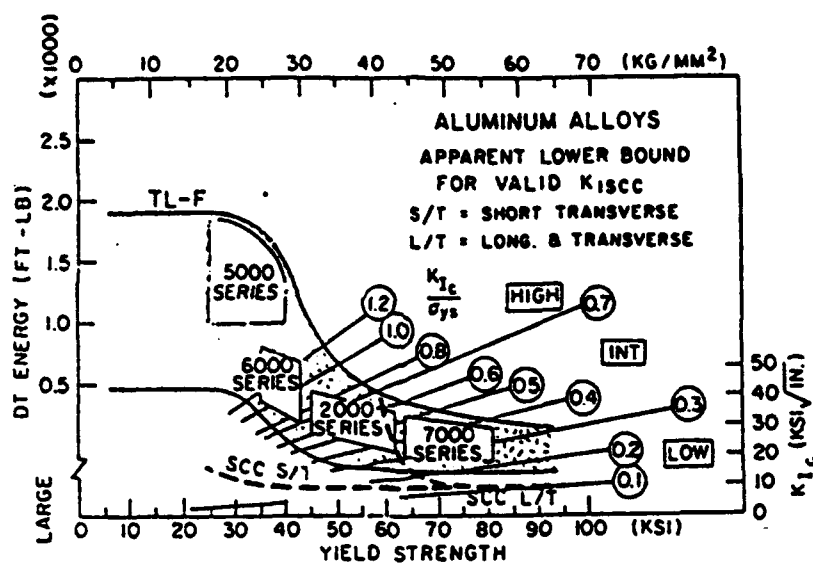Subjected to Tension (After P. C. Paris
and G. C. Sih)

Figure 5 - Ratio Analysis Diagram for Fracture of
Aluminum Alloys (After W. S. Pellini, p. 200)
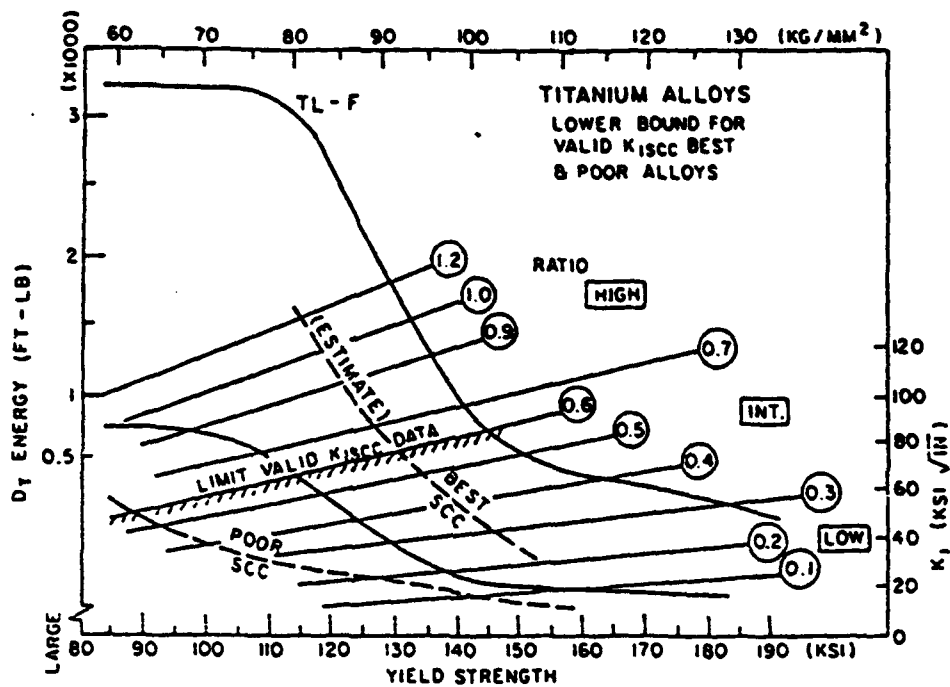
Figure 6 - Ratio Analysis Diagram for Fracture of
Titanium Alloys (After W. S. Pellini p. 200)
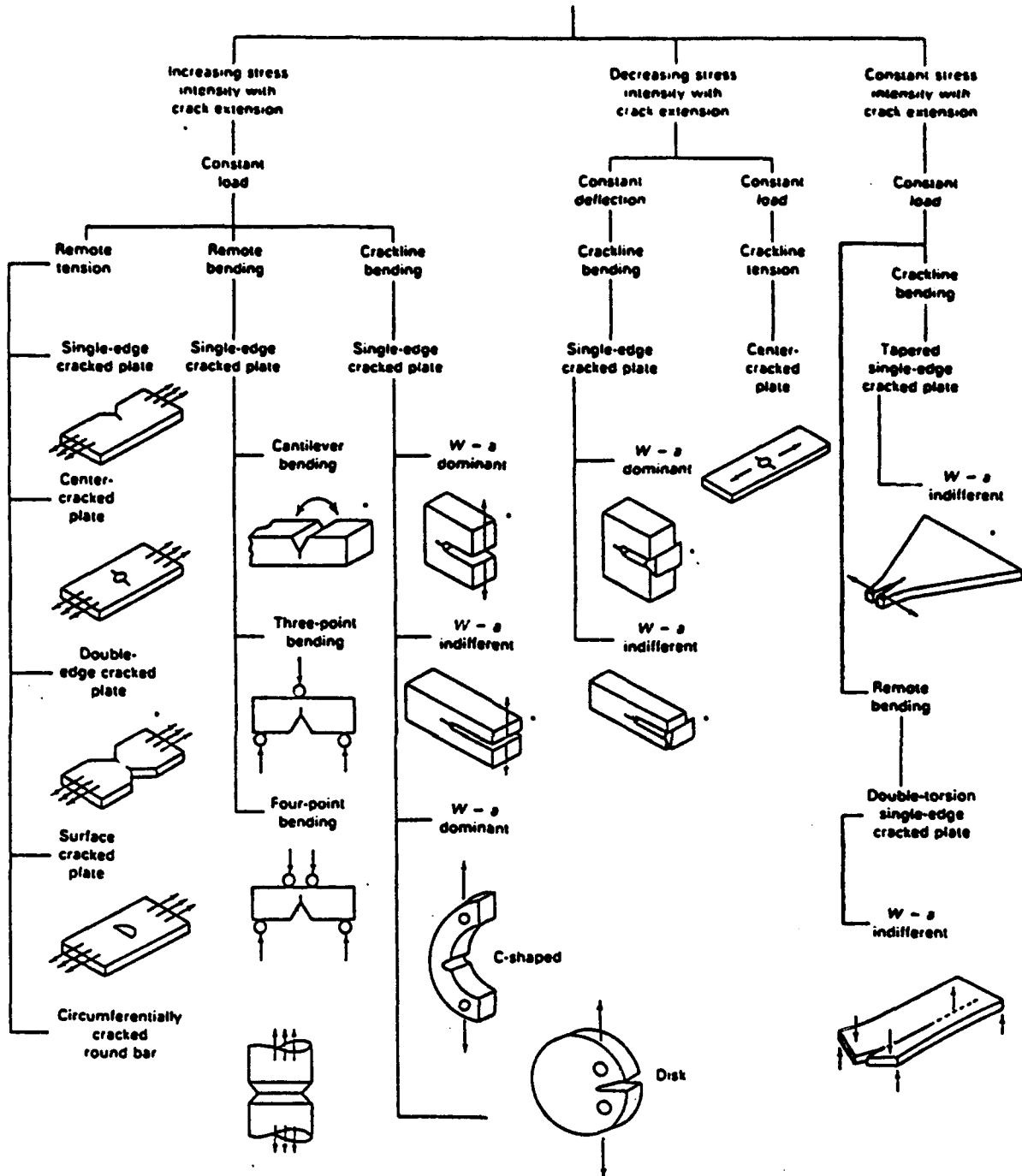
Specimens used in Stress-Corrosion Cracking

Figure 7 - Specimen Configurations for Stress Corrosion Testing.

Approach: Measure KIscc of the steel in the condition used in the fastener... Test in the environment at a potential duplicating the open circuit potential of the coating... Calculate K_{Iscc}/YS... Determine maximum AS/YS (applied stress/yield stress) from chart below for given bolt diameter... Calculate maximum [conservative ($\mu = 0.1$)] installation torque from:

$$T_{i_{max}} \text{ (in-lbs)} \approx 110 \text{ (AS/YS)} \cdot D_{pitch}^3 \text{ (in}^3) \cdot YS \text{ (ksi)}$$
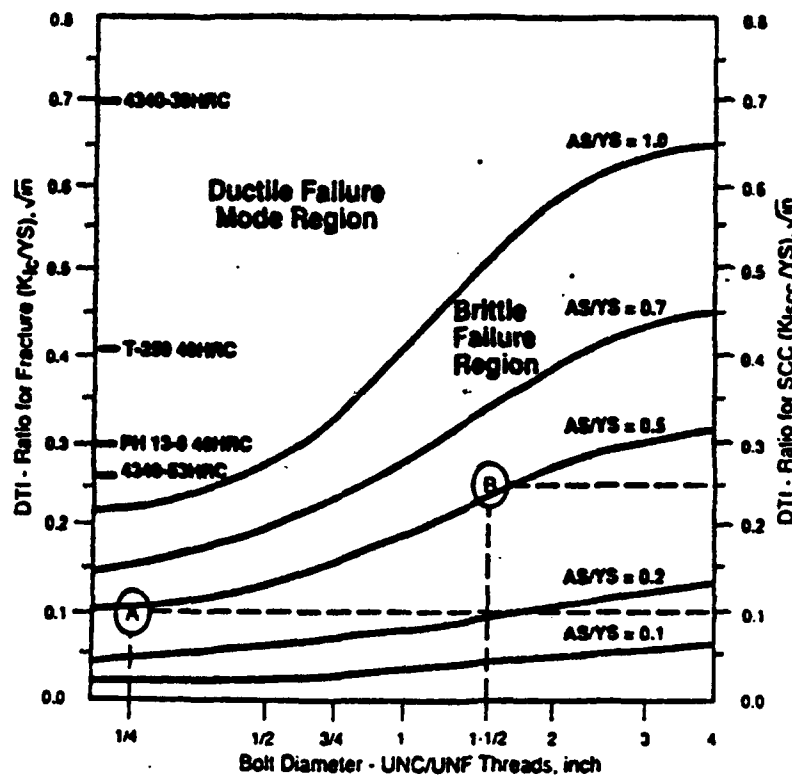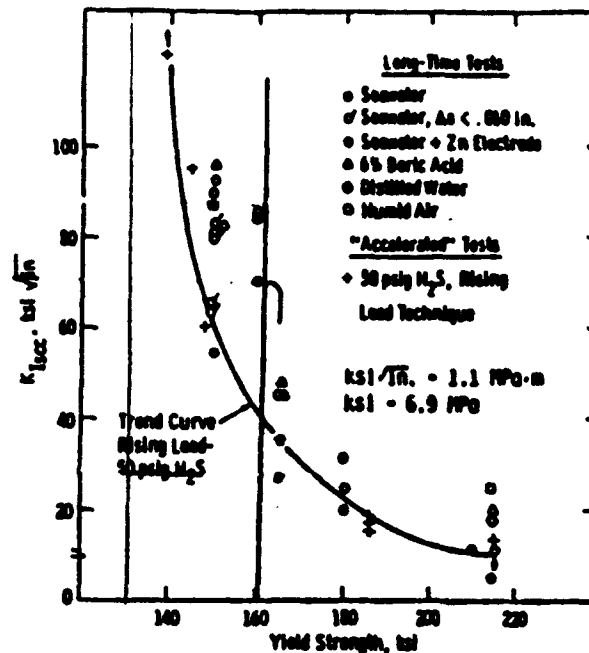

Figure 8 - Demarcation Boundaries Between Ductile and Brittle Failure for a Particular Fastener (After L. Raymond)

K_{Iscc} values of AISI 4340 steel as determined by long-time steady load tests and by rising load tests.

These results demonstrate that the susceptibility of AISI 4340 steel increases with an increase in strength level. It was noted that corrosion fatigue crack growth rates were enhanced considerably in the H_2S environment at stress-intensity levels well below K_{Iscc} so that an apparent immunity under sustained loading does not imply immunity under cyclic loading.

Source: T.T. Shih and W.G. Clark, Jr., An Evaluation of Environment-Enhanced Fatigue Crack Growth Rate Testing as an Accelerated Static Load Corrosion Test, in Environment-Sensitive Fracture, S.W. Denn, E.N. Pugh, and G.M. Uglansky, Ed., STP 821, American Society for Testing and Materials, Philadelphia, 1984, p 325-340.

Figure 9 — Yield Strength with $K_I$scc for 4340 Steel with Superimposed 130 ksi and 160 ksi Yield Strength Lines
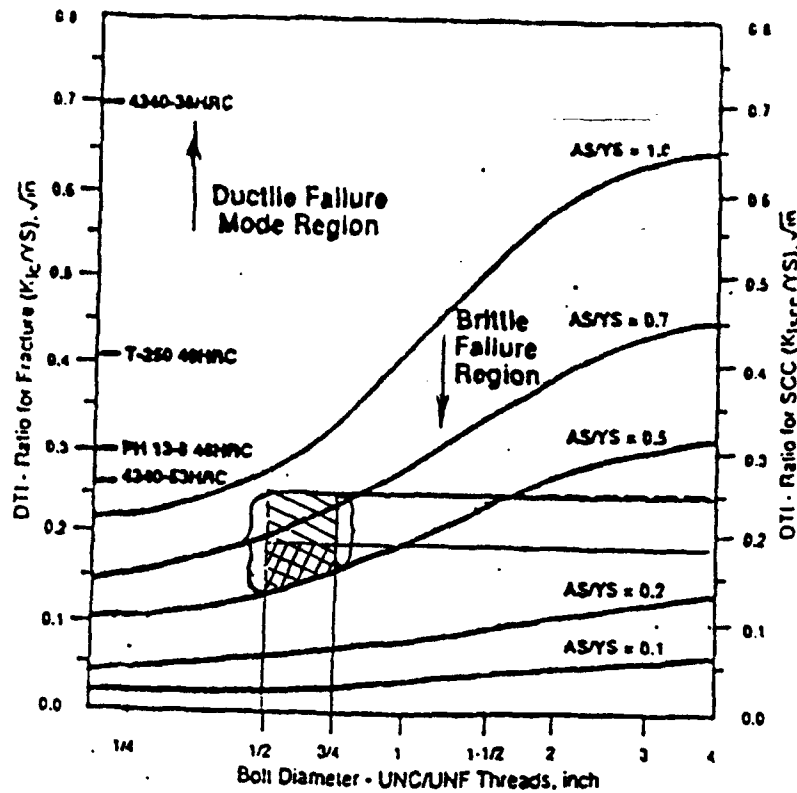
Figure 10 - Graphic Representation of 1/2 to 3/4 in. Dia Bolt
[With the $K_I$scc/Y.S. = 40/160 = .25 and $K_I$scc/Y.S. = 30/160 = .1875 with the concurrent a.s./Y.S. = .5] Showing the Bolt to be Well Within the "Safe" (Ductile Failue) Region. (After L. Raymon)